A 275 channel Whole-cortex MEG System

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Abstract

The design, implementation and performance of a novel whole-cortex MEG system with 275 separate sensing sites is presented. The same design philosophy of firmware synthesis of higher order gradiometers introduced in 1992 with 64 channels has allowed expansion to the present 275 channels, while maintaining excellent white and low frequency noise performance. The system accommodates up to 128 EEG channels, with all MEG and EEG channels sampled synchronously at rates up to 4 kHz. This configuration includes (i) a newly designed digital electronics architecture incorporating DSP/PGA circuitry for uniformity of feedback loop functions, on-line filtering and gradient formation and is structured for future expansion to execute computationally expensive tasks in real time, and (ii) a UNIX- or Linux-based software providing automated tuning, data acquisition and a library of data analyses and visualization features.

1 Introduction

In 1992, a 64-channel whole cortex MEG system was introduced with a unique noise cancellation approach implemented through synthetic formation of higher order spatial gradiometers [1]. Signals from primary sensors are combined in software or firmware using suitable weighting coefficients, with signals from a reference system to form higher gradient response for far field signals (e.g. 2[nd] and 3[rd] order), while maintaining 1st spatial gradiometer response for cortical sources (see **Fig. 1**). The result S of the noise cancellation process, may be written in terms of the primary sensor output σ and N reference outputs r_i (i = 1,..N)

$$S = \sigma - \sum_{i=1}^{N} \xi_i r_i \quad (1)$$

where the ξ_i are weighting coefficients corresponding to the desired gradiometer order [2]. The ξ_i can be determined such that S represents a higher order synthetic

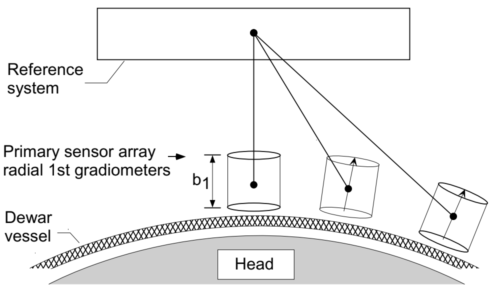

Fig.1 Synthetic gradiometer noise cancellation based on radial 1[st] gradiometers and a reference system consisting of vector magnetometers and tensor gradiometers. The primary sensor baseline b_1 is selected on the basis of optimized sensor signal-to-noise ratio.

gradiometer output, in which case the ξ_i are found to be independent of time, dewar orientation and MEG site noise characteristics. This stability has been amply corroborated over the past decade for about 20 different MEG systems. In situations where the noise is stationary, the coefficients ξ_i may also contain adaptive terms in addition to the gradiometer terms. If the noise is not stationary, the adaptive part of the coefficients ξ_i must be re-evaluated if the background noise changes [2].

Since the introduction of the 64-channel whole-cortex systems, the CTF MEG instruments have evolved toward increased channel density: 143 channels in 1995, 151 channels in 1997 and 275 channels in 2001. The 151- and 275-channel MEG systems allow adjustable orientation of the MEG dewar between 15° and 90° tilt angles from vertical, suitable for MEG measurements on patients in seated, reclining or supine positions [3]. Over the past few years, there has been an increased focus on signal processing techniques for MEG such as beamformers which provide both noise cancellation and MEG source localization. These new methods also provide a rationale for increasing the channel density with the potential for more accurate source mapping and localizations [4]. In the following sections of this paper are presented details of the new 275 channel MEG instrument and its performance.

2 SQUID Sensor System

In this MEG embodiment, the 275 primary sensors are 1[st] order radial gradiometers mounted in a head-shaped array For an approximately hexagonal array of N sensors, with area of head coverage A, the mean spacing between sen-

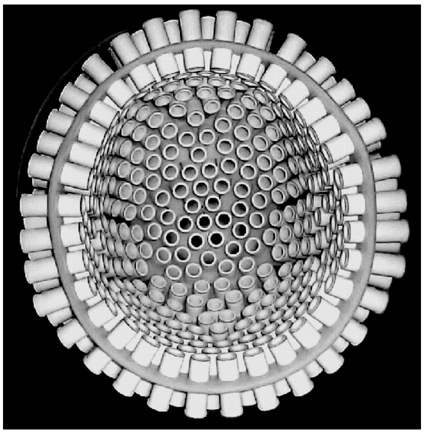

Fig. 2 End (axial) view of the 275-channel MEG sensor array showing 275 radial 1st gradiometers with optimized baselines b_1 = 50 mm and coil diameters = 18 mm, mounted in a rigid helmet-shaped support.

sor centres is given by $e = (2A/(N\sqrt{3}))^{1/2}$. For N = 275 and A = 1200 cm^2, e = 22.4 mm, in good agreement with the measured spacing. An end view of the 275 channel helmet-shaped sensor array is shown in **Fig. 2** which illustrates the emphasis on rigid mechanical design to minimize vibrational noise. The Nb DC SQUIDs fabricated in-house, with white coupled energy sensitivities E_c in the range $1 < E_c < 4 \times 10^{-31}$ J/Hz, are relatively immune to problems associated with trapped flux.

The 29 channel reference system contains a mixture of vector magnetometers and tensor gradiometers whose signals are used in the formation of higher order gradiometers (2^{nd} and 3^{rd}), and also for balancing common mode errors. The higher order gradiometer synthesis significantly reduces environmental noise (see Fig. 4) while maintaining the output and white noise characteristics of the primary sensors on which they are based.

3 Electronics Architecture

A block diagram of the electronics architecture is shown in **Fig. 3**. There are 5 principal blocks in the current modular design: (i) DC SQUID amplifiers, (ii) MEG digital control, (iii) EEG, (iv) Peripheral interface unit, and (v) Digital Signal Processor unit. The miniaturized DC SQUID amplifiers have been assembled in multiple modular units each containing 16 individual amplifiers and all mounted on the MEG dewar top plate. This has been observed to enhance the system stability in the presence of RF interference. The MEG block contains the digital flux lock loops (FLL), and is organized in banks - each bank can accommodate up to 192 channels in twelve 16-channel units. The MEG electronics contains provisions for automated SQUID tuning, deflux control and diagnostics, as well as data communication interfacing and signal processors for real-time computations. 20 bits have been assigned to 1 Φo, and dynamic range is extended to 32 bits, using a ± 1 Φo flux-slip approach [2].

The EEG system is also modular, with 32 channels per unit, and the EEG data are digitized to 21 bits by oversampling. The PIU provides an interface to peripheral equipment such as stimulators, head positioning, head shape digitization and EEG electrode position measurement. The MEG, EEG, and PIU data are then transmitted via fibre-optic links to the PGA/DSP processing unit and are finally acquired by the host computer. Features of the data processing unit include filtering, re-sampling, higher

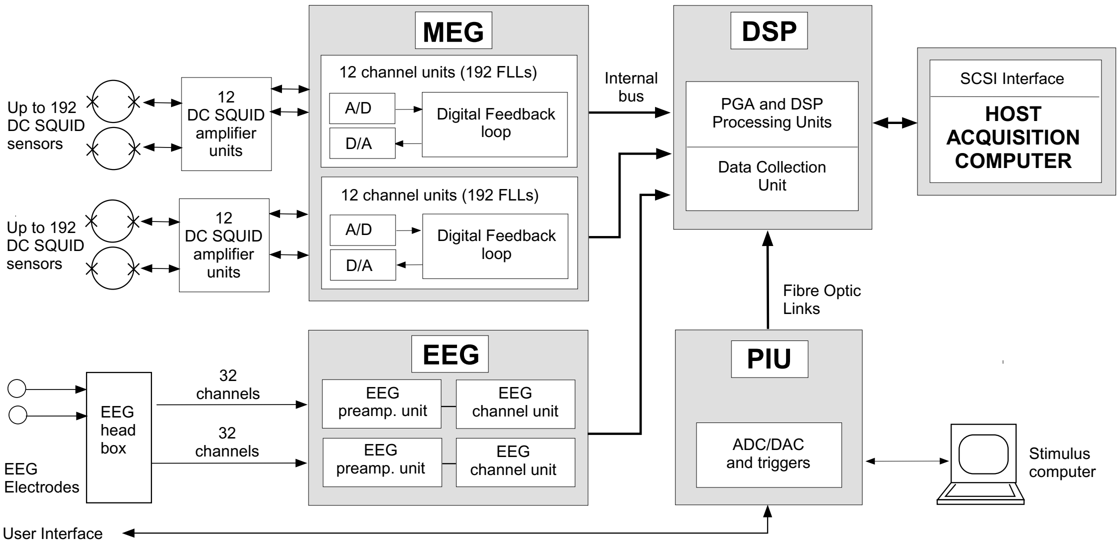

Fig. 3: Block diagram of digital MEG/EEG electronics architecture. A total of 528 channels - 384 MEG, 128 EEG and 16 ADC/DAC channels - can be presently accommodated, and can be sampled at rates up to 4 kHz. The 4 shaded blocks (MEG, EEG, PIU and DSP) are rack mounted and the SQUID amplifier units are incorporated into the MEG dewar top plate. PIU = peripheral interface unit, DSP = digital signal processor, PGA = programmable gate array.

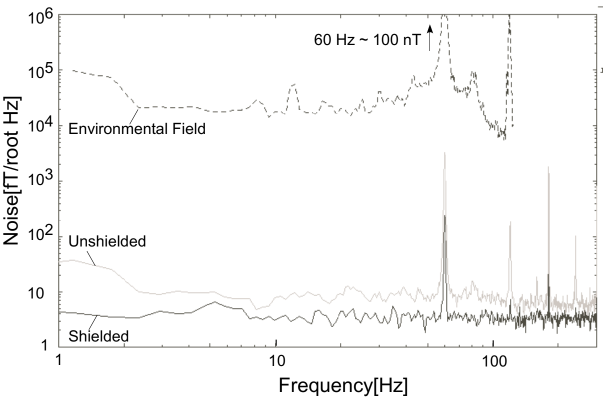

Fig. 4: Noise levels for a typical MEG channel in 3rd gradiometer mode: black - shielded ; gray - unshielded. The upper trace shows the environmental field spectrum where the 60 Hz peak is ≈ 100 nT.

gradiometer synthesis, and there are hooks for expansion to encompass spectral analyses and real-time computation of functions such as covariance and cross-power updates, coherence estimation and spatial filtering.

4 Performance

A comparison of the noise levels achieved in a mu-metal shield and also unshielded in an open industrial environment is shown for a typical MEG channel in **Fig. 4**. The MEG dewar was loosely supported inside a small, tubular μ-metal shield and vibrations caused noise below about 30 Hz. This noise was reduced by synthetic 3rd-order gradiometers and also by adaptive noise cancellation. Reduction of the power line harmonics in the shield is less than in the unshielded environment because the small diameter shield spatially distorts the power line fields. The unshielded MEG channel trace in **Fig. 4** indicates that the system can maintain low noise levels of about 10 fT/√Hz or less, even in the presence of high environmental noise levels where the 60 Hz field was ≈ 100nT.

An example of auditory evoked (AEF) MEG data recorded with the new system is shown in **Fig. 5** where the system was operated unshielded in the same environment as in **Fig. 4**. The auditory stimulus resulted in the characteristic field contour patterns.

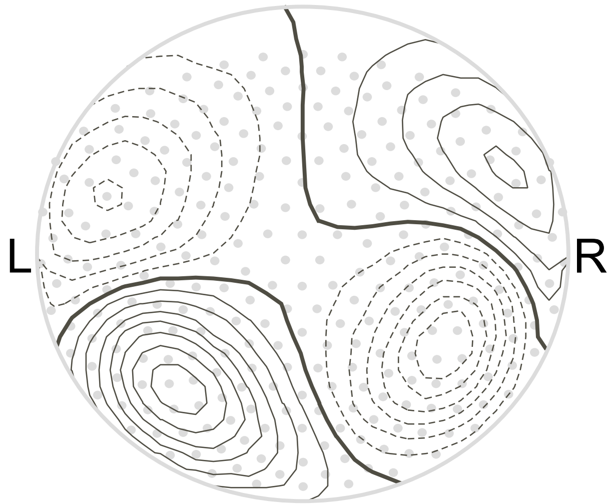

Fig.5 Contour map of AEF response for an adult male. The dots show the locations of the 275 primary sensors. Data recorded at sample rate = 600 Hz, for 1 kHz tones in the right ear. Bandwidth: DC-40 Hz. Contours are spaced at 50 fT. L = left, R = right.

5 Conclusions

The design and performance of a high channel density, whole-cortex MEG/EEG system with 275 separate MEG sensing sites and up to 128 EEG channels has been described. The system displays good noise performance even when unshielded, high slew rates in excess of 100 kΦo/sec, and excellent immunity to RF interference. The modular digital electronics features "set and forget" tuning which results in robust, stable performance and the system can tolerate changing fields of roughly the Earth's field magnitude. The overall system architecture has been designed to accommodate a large number of channels (up to ≈ 500 MEG plus EEG) and also to allow implementation of various real-time and off-line data processing features which enhance the collection and interpretation of simultaneous MEG and EEG data.

6 Literature

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